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About cosmic ray sources with energies up to ($10^{13} \div 10^{15}$) eV

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It is well known that the Sun accelerates charged particles in solar flares. The maximum particle energy detected in the most powerful solar flares was as high as ~ 10^{11} eV. In our Galaxy there is an abundance of active stars, so-called flare stars, that show an activity as our Sun but much stronger. The comparative analysis of solar flares and flares on the yellow and red dwarfs is given. It is shown that the frequency of stellar flares and the energy of particles generated during such processes are enough to provide the energy density of cosmic rays in the disk of our Galaxy.

1. Introduction

It is accepted that the main sources of cosmic rays in Galaxy are supernova star explosions (mainly type II). To provide the cosmic ray energy density $w \approx 0.5$ eV/cm^3 such explosions must occur each ~ (30 - 50) years. In Table the supernova explosions that took place during the last 1000 years together with the data on distances and energy released in cosmic rays are given [1].

Table. Supernova explosions during the last 1000 years.

Supernova	Date	Distance, pc	CR energy, erg
Supernova	1006	—	—
Crab nebula	1054	~ 1100	~ $5 \cdot 10^{48}$
Pulsar 3C58	1181	~ 3300	—
Tycho Brage	1572	~ 360	~ $3 \cdot 10^{46}$
Kepler	1604	~ 1000	~ $6 \cdot 10^{46}$
Cassiopeya	~ 1750	~ 3400	~ $7 \cdot 10^{49}$

It is worth noting that during the last 250 years supernova explosion was not observed in our Galaxy. Although two or three such events could be observed if we take the part of Galaxy restricted by the distance $r \leq 5$ pc from the solar system and suggest that light absorption in this part is weak.

We will consider the cosmic rays in the galactic disk with the sizes: diameter is ~20 kpc and the thickness is ~0.3 kpc. Then the volume of disk is $V_d \approx 10^{11}$ pc^3. The total energy of cosmic rays is $W_{CR} \approx 10^{66}$ eV $\approx 2 \cdot 10^{54}$ erg. If there are other galactic cosmic ray sources besides supernovae they have to give this value of W_{CR}.

2. Stellar activity of yellow and red dwarfs

In Galaxy the total number of stars is ~ $2\cdot10^{11}$ (with the mass equal to the solar one, $M_\odot = 2\cdot10^{33}$ g). The overwhelming majority of the stars (> 90 %) are in the right part of the main sequence. These stars belong to so-called dwarf stars of the *G* - *M* spectral classes. The Sun is a yellow dwarf of *G*2 class [2]. It was established that the great bulk of dwarfs are very active [3].

The main characteristics of dwarf stars are: masses are $(2 - 10^{-3})\ M_\odot$, temperatures are (6000 – 2500) K, luminosities are $(1.5 - 10^{-3})\ L_\odot$ where $L_\odot = 3.86\cdot10^{33}$ erg/s, radii are $(2 - 10^{-3})\ R_\odot$ [3]. As these stars belong to the *G-M* spectral classes they have a low luminosity and can be observed at the distances r < 30 pc. The nearest yellow dwarf, like our Sun, is α Centaur A (class *G*4) at $r = 1.3$ pc. The density of active flare stars in the space near the Sun equals to ~ 0.056 pc^{-3} and the density of all stars is higher in ~ 2 times only.

When powerful solar flare occurs the essential increase of H_α intensity, ultraviolet, radio, *X*- and γ - radiations are observed. Stellar activity of dwarfs is also seen as increases of their luminosities (bolometric, H_α, ultraviolet, radio, *X*- and γ - emissions). Such phenomena are observed on flare dwarf stars. But flare processes on dwarfs are much stronger than on the Sun. If maximum energy released during powerful solar flares is $W \le 10^{32}$ erg flare stars give the energy up to $W \approx 10^{36}$ erg or more (e.g. T-Taurus produce flares with the energy release up to 10^{39} erg [4]). The flare stars radiate powerful *X* – ray flux. For example, the ratio of flare star emission in the interval of $\lambda = (1 - 8)$ Å to bolometric one is $(L_X/ L_B) \approx 10^{-6}$ and the same value for the Sun is only $(L_{\odot X}/ L_{\odot B}) \approx 10^{-9}$.

On flare stars there are spots like sunspots. On the sun total sunspot area occupies less than 0.5 % of the solar surface but total starspot area on the flare stars occupies from ~ 10 % to 90 % of the stellar surface. Like 11-year solar activity cycle flare star activity also has quasi-periodicity with the different periods.

The strength of magnetic field in active regions of the Sun can reach ~ (3 – 4) kGs. The magnetic fields of flare stars are not measured but one can expect much stronger magnetic fields in the active regions of these stars (up to several tens of kGs). These stars have much stronger stellar winds in comparison with our Sun.

The large areas of spots on yellow and red dwarfs with strong and complex magnetic structures produce a large amount of stellar flares. If, in average, the Sun gives about one powerful solar flare per year on dwarf flare stars such events occur each day or each hour. For example, UV Get dwarf produce flares almost each hour (UV Get is at $r \approx 2.7$ pc, $\log L_{UV} = 30.91$). The duration of flares taking place on flare stars covers the time intervals from several second up to several hours. As a whole, flare activity of dwarfs is higher than flare activity of the Sun in ~ 10^4 times and energy released in flare processes is higher in the same times.

It is difficult to believe that the high stellar activity of yellow and red dwarfs will not produce charged particle acceleration in flare processes [5, 6]. Thus, we suppose that flare stars accelerate charged particles as our Sun does.

3. Maximum energy of particles accelerated by flare stars

Let us evaluate the maximum energy of charged particles W_{max} accelerated in stellar flares of yellow and red dwarfs. At first, the value of W_{max} will be found for solar flares. To do it the model with the formation of the current sheet during solar flare development will be used [7].

In this model current sheet is formed in the solar corona above photospheric active region where there is complex structure of magnetic fields and plasma motion. The particle acceleration takes place in electric field of current sheet. The value of W_{max} can be evaluated as

$$W_{\max} = q \cdot L \cdot E\,; \qquad E = -\frac{1}{c}[V \times B]; \qquad V \le V_A = \frac{B}{\sqrt{4\pi\rho}}\,,$$

where q – electric charge of particle, L – length of current sheet, E – electric field strength, V – plasma velocity, B – magnetic field strength, V_A – Alfven's velocity, $V \le V_A$, ρ - plasma density, $\rho = m_H \cdot n$, m_H – hydrogen atom mass, n – atom concentration. For the Sun we take $q = 1$, $L = 10^{10}$ cm, $B = 300$ Gs, $n = 10^{10}$ cm^{-3} then $V_A = 6.5 \cdot 10^8$ cm/s, $E \approx 2 \cdot 10^3$ V/cm. When $V \approx V_A$, we have $W_{\max} \approx 2 \cdot 10^{13}$ eV.

For flare stars the magnetic field is much stronger. If we take $B = 3000$ Gs then $W_{\max} \approx 2 \cdot 10^{15}$ eV, that is, the flare stars could accelerate particles up to the "knee" of energy cosmic ray spectrum.

4. Is power of flare stars enough to provide cosmic ray energy in Galaxy?

The energy of cosmic rays in our galactic disk is evaluated as $W_{CR} \approx 2 \cdot 10^{54}$ erg. In Galaxy the total number of stars is $N \approx 2 \cdot 10^{11}$. We take that 10 % of that number are flare stars ($N_F \approx 2 \cdot 10^{10}$) and the averaged energy P released in cosmic rays during one flare is about $P \approx 2 \cdot 10^{35}$ erg. We take that flare star can produce one such flare for several days. Then the energy of cosmic rays released by flare stars is defined as

$$W_{CR} = P \cdot N_F \cdot \nu \cdot \tau\,,$$

where ν - flare frequency (~ 36 flares per year), $\tau \approx 10^7$ yrs - lifetime of cosmic rays in Galaxy. The evaluation gives $W_{CR} \approx 1.4 \cdot 10^{54}$ erg. This value is comparable with the figure given above.

Thus, flare stars can produce cosmic rays and the power of these stars is enough to provide the necessary energy of cosmic rays in Galaxy.

5. Anomaly component of cosmic rays (ACR)

The ACRs were discovered in 1972 [8]. The ACRs represent as a rule single ionized atoms of He, O, N and some other elements with energies from several MeV/nucleon to several tens of MeV/nucleon. They are strongly modulated by solar activity. In Figure 1 the time dependences of anomalous oxygen with E = (8 – 27) MeV/nucleon and flux of cosmic ray particles with E = (0.1 –1.5) GeV are given [9, 10]. The amplitudes of modulation of ACR particles and low energy GCR in the 11th solar activity cycle are more or less comparable.

The explanation of ACR existence was given in [11]. It includes the penetration of neutral atoms from interstellar space into heliomagnetosphere, ionization of these atoms near the sun by solar ultraviolet radiation. After that the ionized atoms are picked up by solar wind and are transported to the heliomagnetospheric termination shock. The termination shock accelerates some part of these ionized atoms up to energies of several MeV/nucleon forming ACR flux. However, till now the effective mechanism of ionized atoms acceleration is absent. Furthermore, at the distances up to ~ 85 a.u. the termination shock was not discovered or if it was but very weak [12, 13].

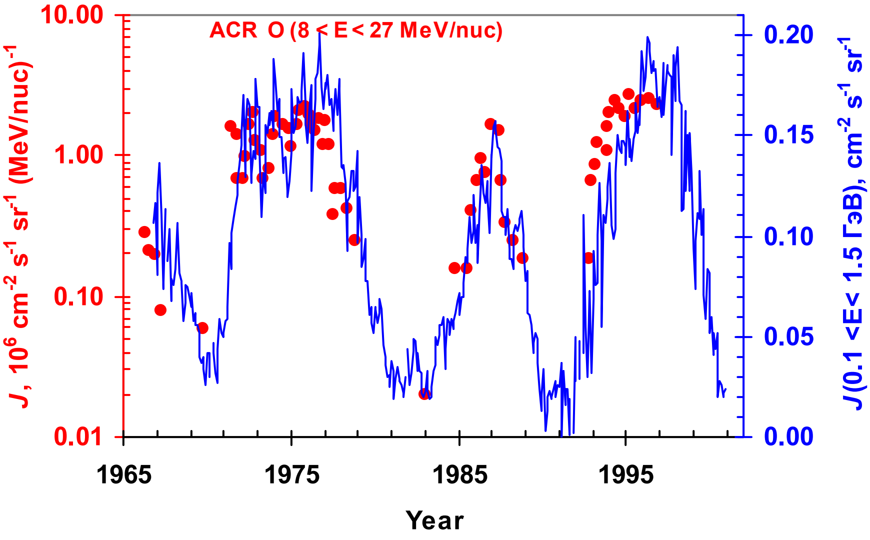

Figure 1. Time dependences of ACRs (points) and galactic cosmic ray flux (curve) [9, 10].

The flare stars could produce of ACRs as our Sun accelerates non-full ionized atoms in solar flares. In this case to avoid the ionization during the propagation of ACRs in the interstellar medium the sources of these particles have to be at the distances less than (30 ÷ 40) a.u.

3. Conclusions

Flare stars could produce galactic cosmic rays and provide the necessary density of cosmic ray energy in the galactic disk. Also, these stars could be responsible for the anomaly cosmic ray production.

References

[1] V.L. Ginsburg, S.I. Syrovatsky, Origin of cosmic rays, Moscow, Nauka (1963), (in Russian).
[2] T.A. Agekyan, Stars, galaxies, metagalaxies, Moscow, Nauka, 419 p. (1982), (in Russian).
[3] R.E. Gershberg, Solar type activity of stars laying on the main sequence, Odessa, Astroprint, 688 p. (2002) (in Russian).
[4] V.G. Gorbatskii, I.N. Minin, Non-steady-state stars, Moscow, 356 p. (1963), (in Russian).
[5] V.P. Grinin, V.V. Sobolev, Astrophysics, 13, 887 (1977) (in Russian).
[6] V.P. Grinin, V.V. Sobolev, Astrophysics, 28, 355 (1988) (in Russian).
[7] A.I. Podgorny, I.M. PodgjonyY. Bull. of the Russian Academy of Sci., Physics (1997), 61, No. 6, 837.
[8] M. Garcia-Munoz, G.M. Mason, J.A. Simpson, 13th ICRC, USA (1973), 2, 1304.
[9] R.A. Mewald, R.S. Selesnick and J.R. Cummings. Preprint, USA (1995), SRL-96-04, 23.
[10] Yu.I. Stozhkov et al., Solar Physics (2004), 224, Nos. 1-2, 323.
[11] L.A. Fisk, B. Koslovsky and R. Ramaty. Astrophys. J. (1974), 190, L35.
[12] R.B. Decker et.al., 29th ICRC, Tokyo (2003), 7/7, 3769.
[13] F.B. McDonald et al., 29th ICRC, Tokyo (2003) 7/7, 3763.